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Science & Technology Facilities Council ISIS

# Accelerator design of nuSTORM

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on behalf of nuSTORM study team

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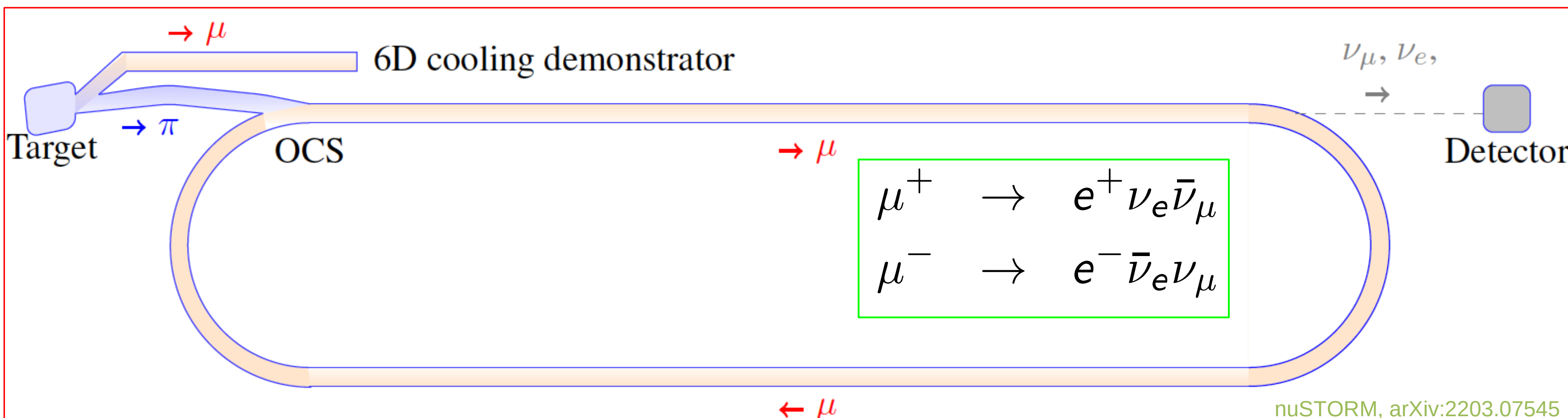
# Outline

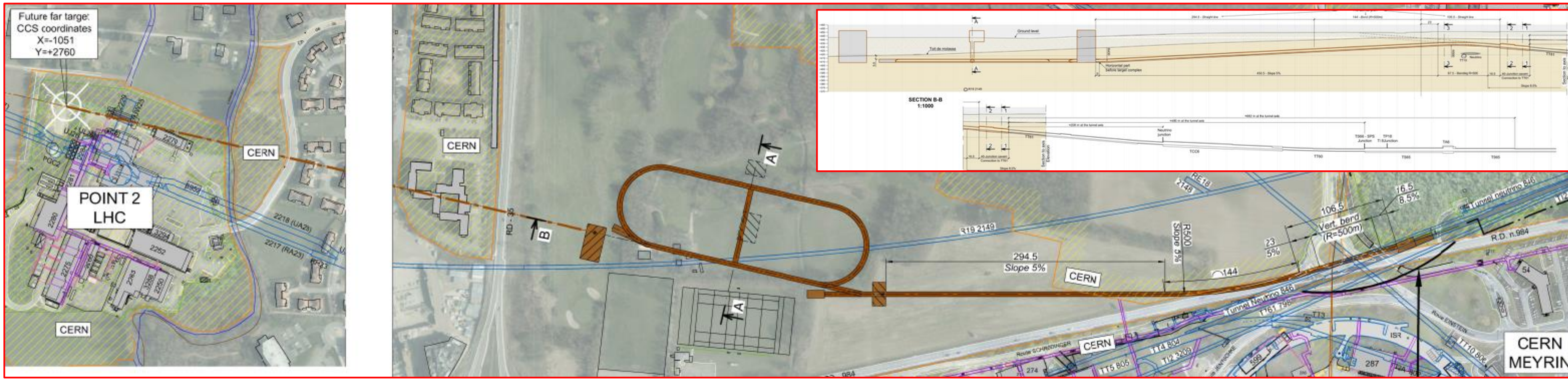
- Introduction
- nuSTORM at CERN
- Studies of hybrid FFA solution
- Recent studies of beam capture, transport and injection
- Summary and future plans

# Introduction

- nuSTORM (`NeUtrinos from STORed Muons') is a facility based on a low-energy muon decay ring.
- Can use existing proton driver (like SPS at CERN)
- Conventional pion production and capture (horn)
  - Quadrupole pion-transport channel to decay ring with large momentum acceptance (±10%)
  - Direct injection of pions into the decay ring to form circulating muon beam subsequently used as a source of neutrinos w/o a kicker
- Variable energy operation **(1 < $E_\mu$ < 6 GeV)**
- Initially proposed at FNAL, now working towards the conceptual design for CERN



# nuSTORM at CERN




- Extraction from SPS through existing tunnel
- Siting of storage ring:
  - Allows measurements to be made 'on or off axis'
  - Preserves sterile-neutrino search option

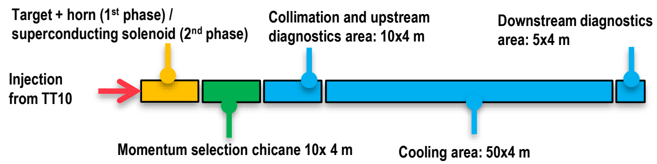
# SPS feeding option

Key beam parameters foreseen for nuSTORM (based on the analysis of CENF.)

| | |
|---|---|
| Momentum | 100 GeV/c |
| Beam Intensity per cycle | $4 \times 10^{13}$ |
| Cycle length | 3.6 s |
| Nominal proton beam power | 156 kW |
| Maximum proton beam power | 240 kW |
| Protons on target (PoT)/year | $4 \times 10^{19}$ |
| Total PoT in 5 year's data taking | $2 \times 10^{20}$ |
| Nominal / Maximum repetition rate | 6/3.6 s |
| Max. normalized horizontal emittance (eh at 1 $\sigma$ s) | 8 mm.mrad |
| Max. normalized vertical emittance (ev at 1 $\sigma$ ) | 5 mm.mrad |
| Number of extractions per cycle | 2 |
| Interval between extractions | 50 ms |
| Duration per extraction | 10.5 $\mu$s |
| Number of bunches per extraction | 2100 |
| Bunch length (4s) | 2 ns |
| Bunch spacing | 5 ns |
| Momentum spread (dp/p at 1s) | $2 \times 10^{-4}$ |

International MUON Collider Collaboration

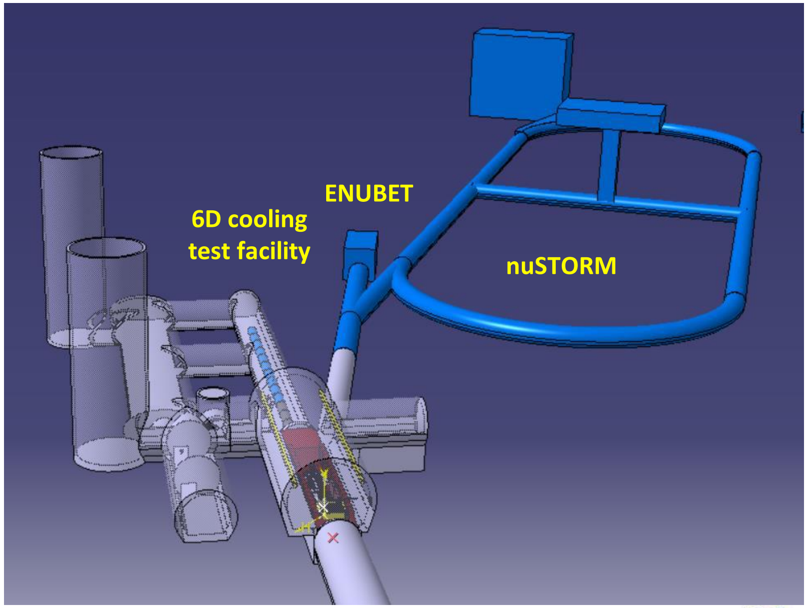
# Conceptual layout




Under discussion!

## MUC Demonstrator

- The Facility is flexible enough to accommodate other experiments.
- nuSTORM and potentially ENUBET could be branched from the MUC Demonstrator Facility.
- The same target complex would be used profiting from its shielding and general target systems infrastructure, utilities, and accesses.
- The double deflection of the beamline could reduce radiation streaming towards the nuSTORM ring.
- Synergies between experiments would reduce costs on both sides.
- Is the 26 GeV/c beam from the PS appropriate for these two experiments?



# Storage ring designs

- FODO design (example: A. Liu's design)
  - Separate-function magnets
  - Relative momentum acceptance ~±9%
  - Large, natural chromaticity, some losses induced by resonances
  - Zero dispersion in the injection/production straight
    - Good efficiency of muon storage and neutrino production
- Full FFA (Fixed Field Alternating gradient) design
  - Combined function magnets
  - Relative momentum acceptance ~±16% or more
  - Zero chromaticity, no resonance crossing
  - Small dispersion and scalope angle in the the injection/production straight
    - Reduced efficiency of muon storage and some effects on the neutrino spectrum
- Hybrid design
  - Combined function magnets in the arcs and in the return straight, quads in the injection/production straight
  - Relative momentum acceptance ~±16%
  - Relatively small chromaticity originating from the injection/production straight
    - Tune spread between integer and half integer lines
    - Some extra correction possible
  - Zero dispersion in the injection/production straight
    - Good efficiency of muon storage and neutrino production

# Hybrid design assumptions

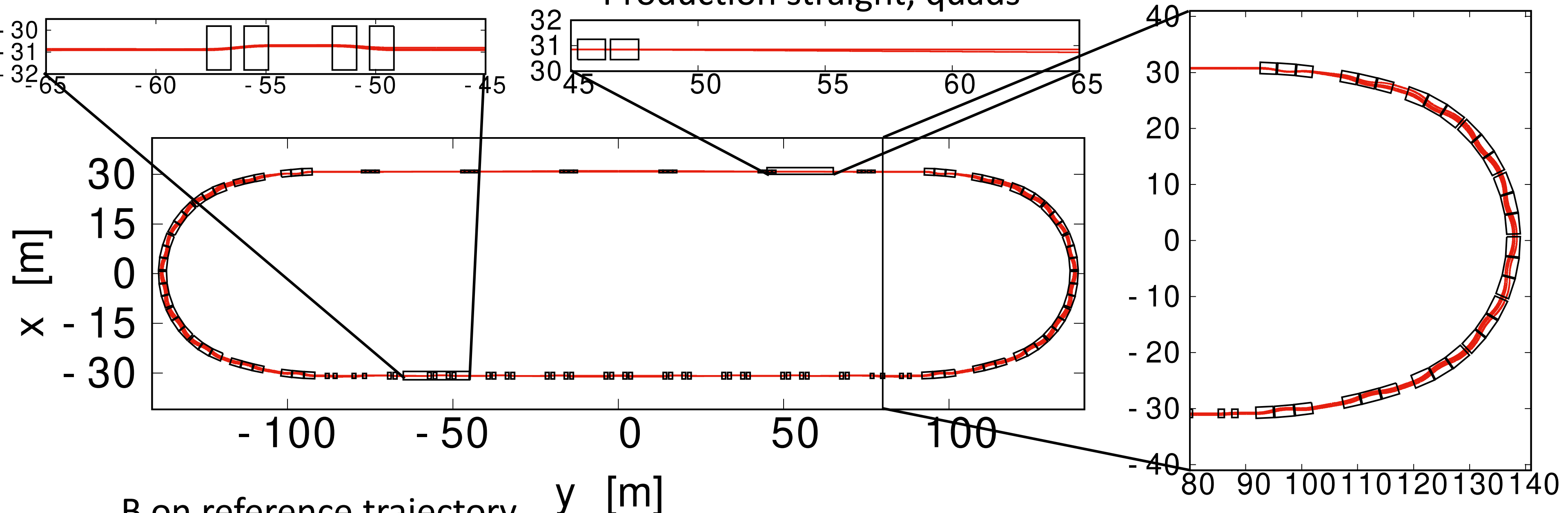
- Long straight sections kept at 180m (as in FNAL designs)
- Arc modified to accommodate higher momentum (up to 6.5 GeV/c orbit)
- Dispersion in the arcs is kept smaller to reduce the magnet aperture
- FFA parts (both arcs and straight FFA) were made with a fully transparent optics (both phase advances modulo $\pi$).
- For the quad production the solution made of regular cells is selected
- Extra matching sections added in the straight FFA part

# Hybrid design

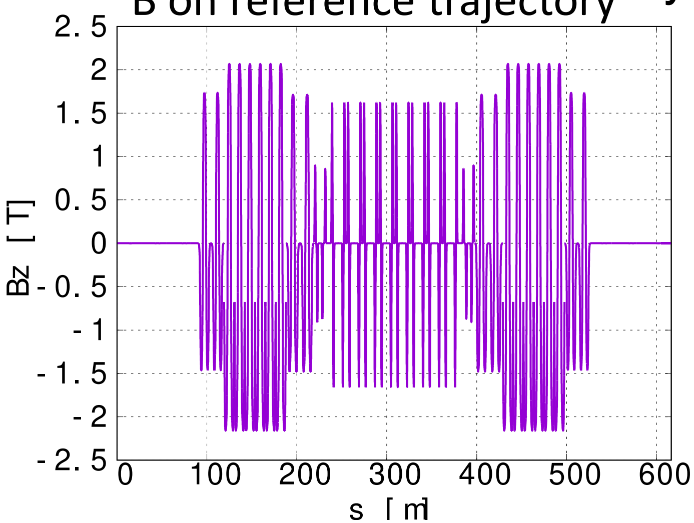
Arc with two matching sections, FFA magnets

Straight FFA

Production straight, quads




B on reference trajectory




- SC magnets in the arcs
- NC magnets in the straights
- Several types of the lattice cells combined
- Injection in the dedicated straight at the end of the arc

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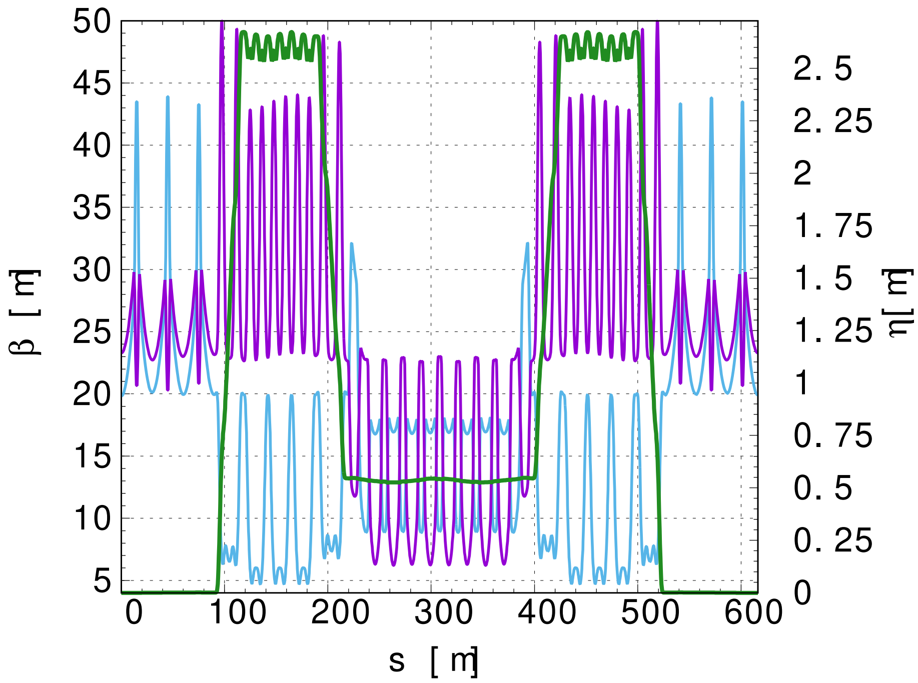
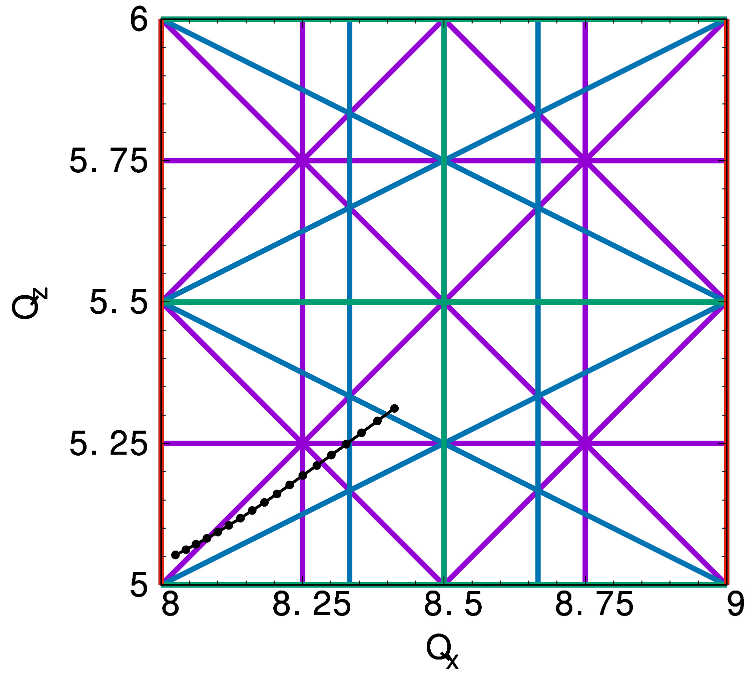
# Hybrid optics

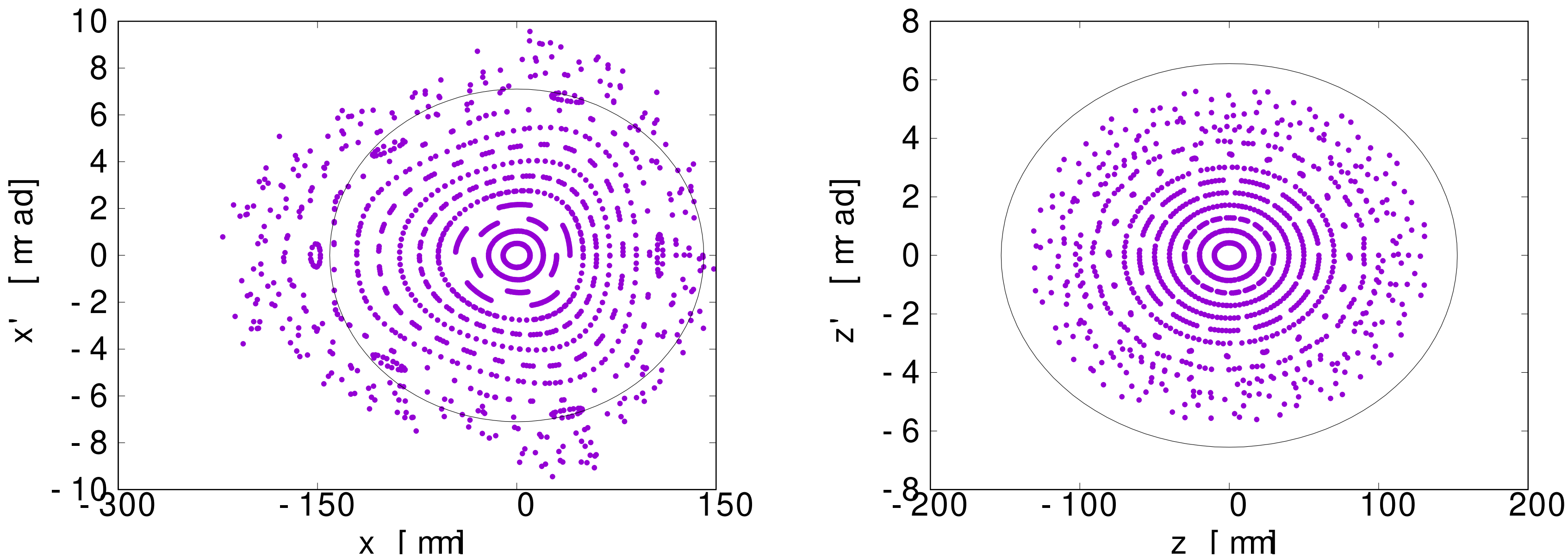



- Good dispersion matching to zero in the production straight
- Relatively large beta functions in the production straight for good neutrino production efficiency

Tune shift for ±16% relative momentum spread

# Hybrid ring, tracking




- Good DA in both planes
- Cross check with PyZgoubi (work in progress)
- Tracking with the full beam distribution (next step)

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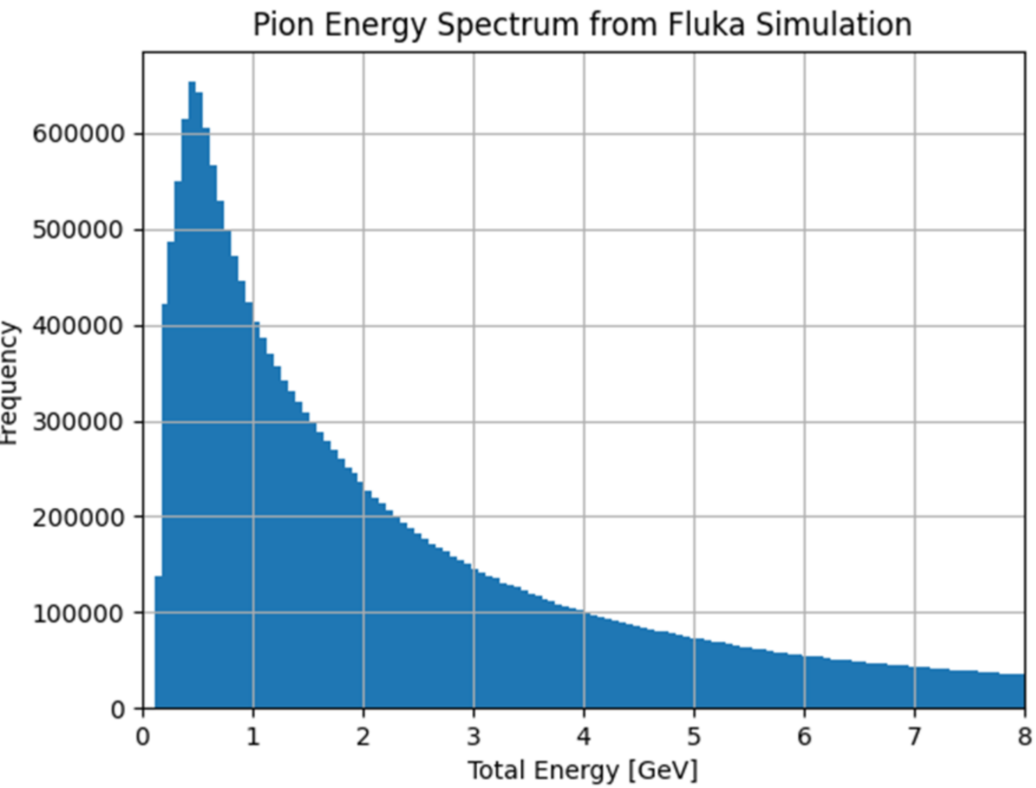
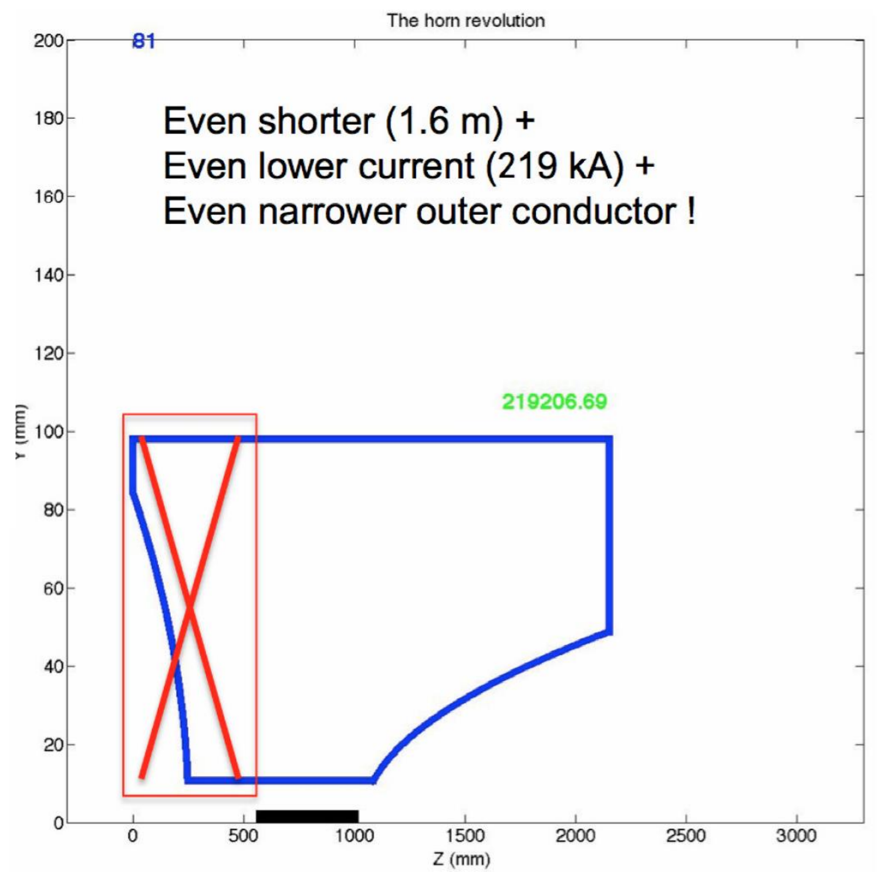
# Current focus and near future plans for Hybrid design

- Work on the Hybrid FFA design:
  - Cross check between codes
  - Possibly a modest chromaticity correction to reduce the tune spread to ~0.2
  - Further design work on injection
- Evaluation of the performance: momentum spread, DAs, transmission and the neutrino fluxes, and comparison with other lattices (FODO, full FFA).

# Target and horn simulations



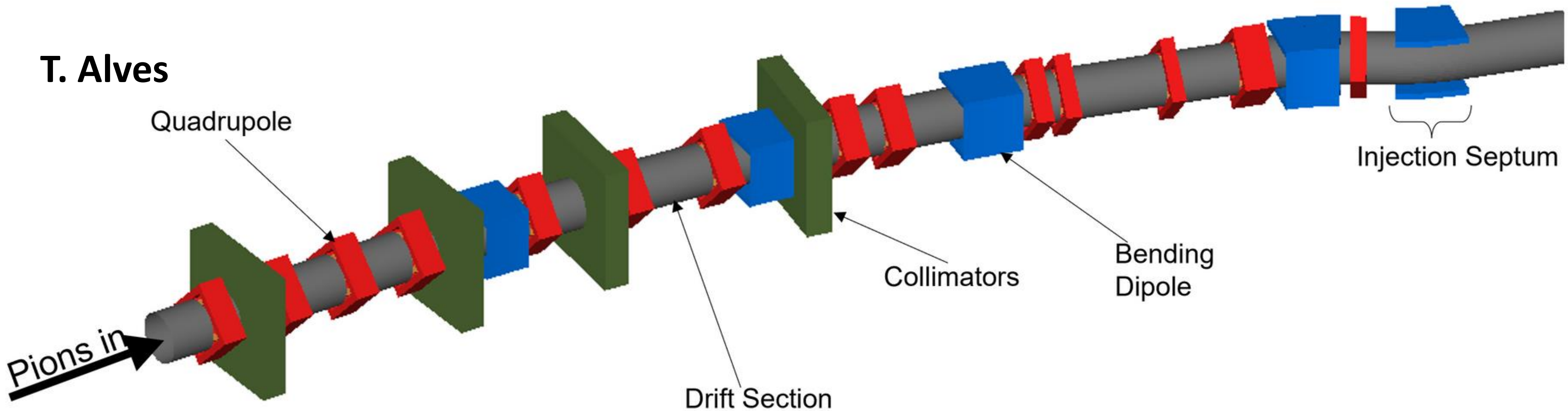

Horn geometry (Tupri005, IPAC'14)



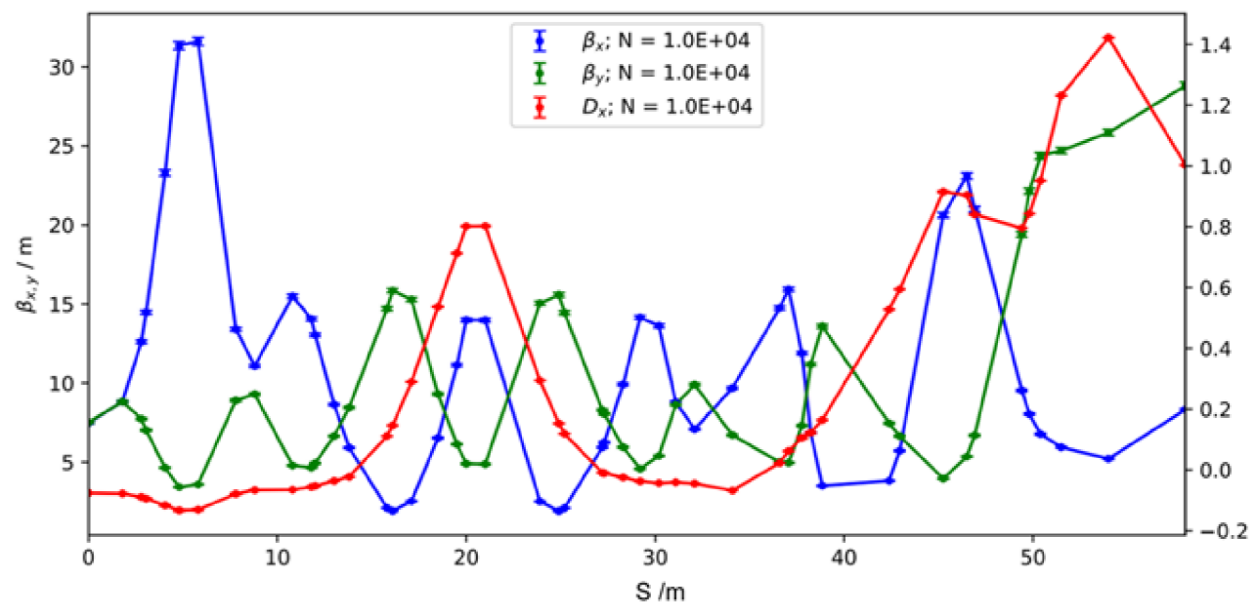

- Target simulated in FLUKA (J. Back)
- Parameters of the target adopted from the FNAL study
  - Inconel target, 46cm in length
- Horn geometry and current adopted from the FNAL study (A. Liu)

# Pion beam line simulation in BDSIM

**T. Alves**




Layout of pion injection line




Betatron functions and dispersion for pion beam from the horn until the injection point in the nuSTORM ring calculated by tracking in BDSIM

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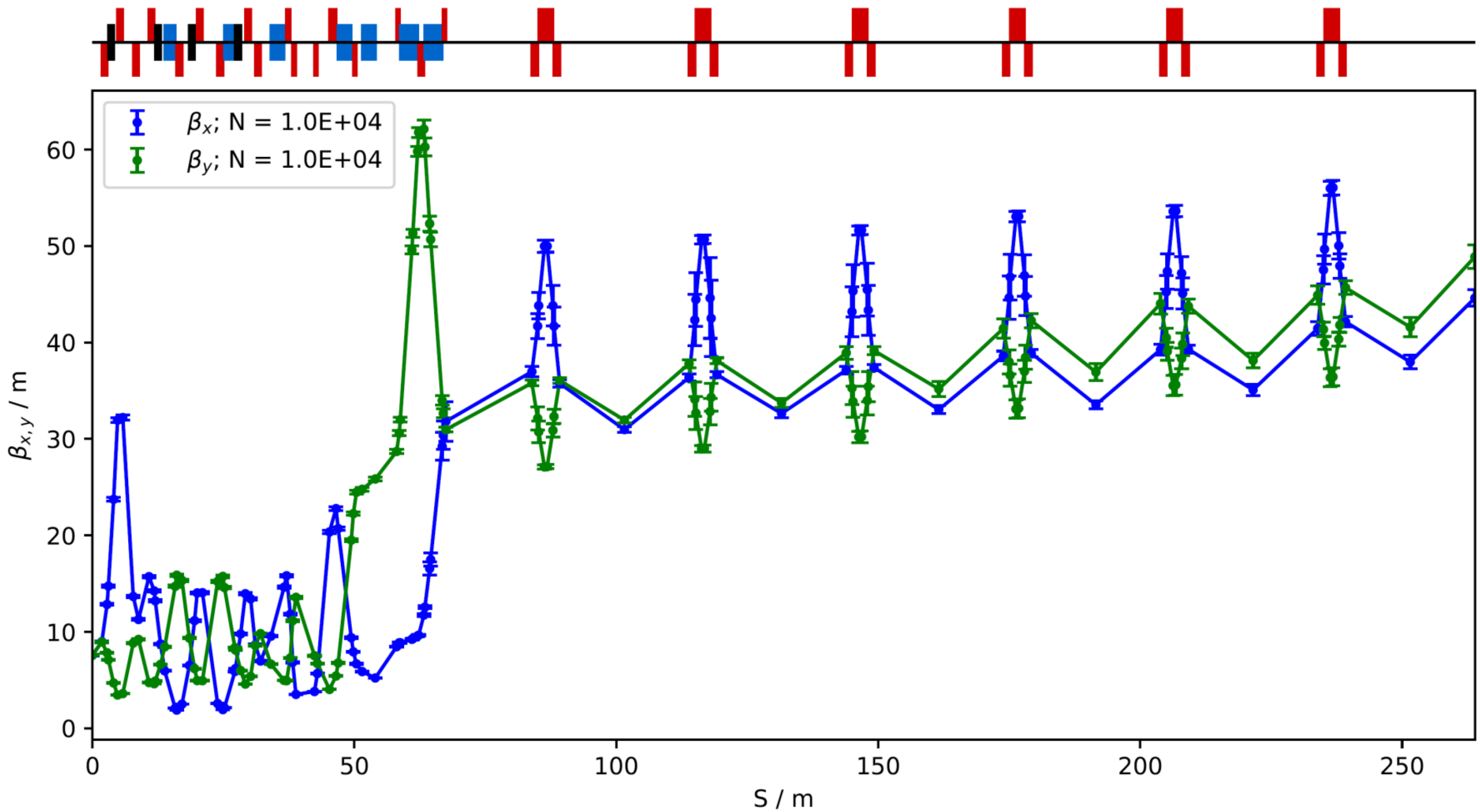
# BDSIM study extended till the end of the production straight




Betatron functions of pions from the horn until the end of the production straight in the nuSTORM ring calculated by tracking in BDSIM

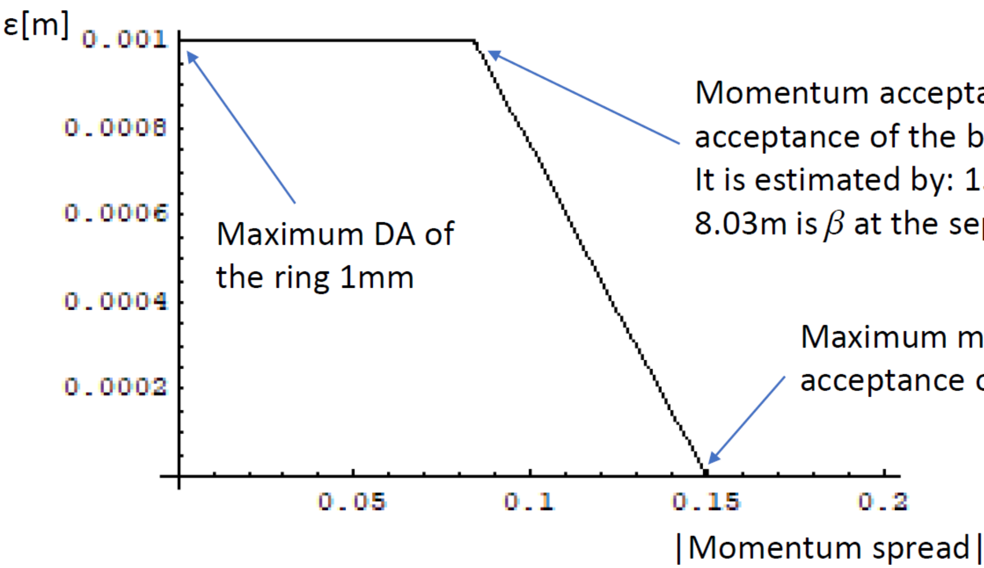
# Acceptance cut at the end of the quad straight

- $\frac{x^2}{\beta_x^q} + \beta_x^q (\frac{p_x}{p_z})^2 \leq \varepsilon(|\frac{\Delta p}{p_0}|)$

$\frac{\Delta p}{p_0} = \frac{p - p_0}{p_0}$

$p_0$=3.8 GeV/c (muon central momentum for 5 GeV/c pions injection)

$\beta_x^q$=19.98m (periodic beta of the quad straight)




Momentum acceptance at which septum starts to limit the acceptance of the beam in the ring ~8.41%.
It is estimated by: 15%-Sqrt[0.001*8.03]/1.36,
8.03m is $\beta$ at the septum, 1.36m is D at the septum

Maximum momentum acceptance of the ring 15% (16% used in the calculations)

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# PS/SPS feeding comparison

**T. Alves**

| Proton Energy on target | $\pi^+$ Central Momentum | $\mu^+$ Central Momentum | Starting $\pi^+$ | Undecayed $\pi^+$ at end of decay straight | Total $\mu^+$ produced | Accepted $\mu^+$ |
|---|---|---|---|---|---|---|
| $100GeV$ | $5GeV/c$ | $3.8GeV/c$ | $986,303$ | $221,718$ | $192,932$ | $19,074$ |
| $100GeV$ | $7.2GeV/c$ | $5.42GeV/c$ | $834,311$ | $255,522$ | $156,019$ | $24,694$ |
| $100GeV$ | $2.64GeV/c$ | $2.0064GeV/c$ | $746,499$ | $65,540$ | $90,593$ | $2,187$ |
| $26GeV$ | $5GeV/c$ | $3.8GeV/c$ | $230,775$ | $53,484$ | $47,438$ | $4,650$ |

- Simulation performed using FLUKA and BDSIM assuming $10^7$ POT
- Horn current scaled with momentum
- Low pion momentum setting (2.64 GeV/c) requires further investigation due to high losses in the pion beam line (work in progress)
- Results will be used for the neutrino flux normalisation

# Summary

- Solid design exist and could be implemented straightaway
- FFA design allows to substantially increase the ring's momentum acceptance (and so the neutrino flux), while maintaining a very large transverse acceptance
- Novel Hybrid ring shows very promising results and we are working to demonstrate its performance.
  - We are working towards the full BDSIM model
- New ideas to combine nuSTORM, ENUBET and Muon Collider Demonstrator facility
  - Main difficulty is the different preferred extraction methods (fast – nuSTORM and Muon Collider Demonstrator, and slow – ENUBET)
- Promising recent progress on pion capture, transport and injection
  - Further work on low energy beam capture and transport is needed to demonstrate variable energy operation (for the mean muon storage momentum ~1GeV/c to ~6 GeV/c)